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To

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George C. Marshall Space Flight Center

Marshall Space Flight Center

Alabama

(NASA-CR-144008) DESIGN AND FABRICATION OF
AN END EFFECTOR Final Report (Massachusetts
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From

The University of Massachusetts

FINAL REPORT

DESIGN AND FABRICATION OF AN END EFFECTOR

By Professor F.R.E. Crossley in conjunction

with Professor Franklyn G. Umholtz

Dated: May 21, 1975

NASA Contract No. NAS 8-29073

COTR - Mr. James W. Patterson

Entitled: "Definition, Design and Fabrication of a Working Model of a
General Purpose End Effector for a Remote Controlled Manipulator"



Final Technical Report

In the course of this project the following have been delivered to George C. Marshall Space Flight Center.

- 1) A Report entitled "On the Current State of the Art of Design of General Purpose Mechanical End Effectors, for a Remotely Controlled Manipulator."

This survey paper in two parts, included 33 photographs of different end effectors. The first part of this report was presented by request to the RMS/EVA Committee of NASA (Dr. Stanley Deutz, chairman) at their meeting at JPL, Pasadena, California, on September 12, 1972.

The second part was a Master's degree Thesis by Mr. Frank Skinner.

- 2) One prototype model of a mechanical end effector, to be mounted distal to the wrist joint of a mechanical arm, fulfilling the contract.
- 3) A set of both detail and assembly drawings of the above end effector.

And now here we attach:

- 4) A technical paper entitled "Design for a Three Fingered Hand."

An abstract of this paper has already been accepted for presentation to the "Second Conference on Remotely Manned Systems -- Technology and Applications" (Professor Ewald Heer, Chairman) to be held in

June 1975 at the University of Southern California. The paper, authored jointly by Professors Crossley and Umholtz, is under consideration for publishing in the full Proceedings of this conference.

This paper describes our final product which you now have and are testing.

As written up in the paper, the hand was designed for the following capabilities, to wit:

- 1) To have a standard parallel-jaw grip like any other end effector, between thumb and index;
- 2) To be able to grasp also cylindrical objects and balls;
- 3) With use of the thumb nail, to be able to pick up a flat steel rule or a needle from a table;
- 4) To pick up a hammer or a screwdriver from a table, using thumb and index fingers, then by use of the third finger to reach around this object already held and pull it into a firm grasp nested in the palm, firmly enough that the hammer can be swung to drive large nails into a piece of wood,
- 5) To pick up a portable electric drill with thumb and ring finger, and pull the trigger to operate with the index finger.

All these operations were successfully made using our penultimate model. We were not able to test the final model because it would not mount properly on the Los Amigos arm.

We feel that the final model may not be quite as successful as the earlier one on which it was based; because the dimensions of the fingers were changed a very little. The velocity ratios of the electric motors were also changed in order that they should move a little more speedily.

We also feel that two mistakes were made in the final revised design: (a) It was not so good that all the mechanisms of the fingers should be enclosed. The palmar surfaces could have been a flexible strip and the dorsal aspect either open or with a cover plate. Then the fingers would have been much lighter and more flexible. And (b) the thumb nail should not have been motorized. The actuation of the thumb nail could have been by way of a slide-bolt, whose knob protruded enough that the robot could knock it in or out. That would have been sufficient, we believe. The additional motor adds to the weight, and protrudes into the palm space.

Plans for another model based on our experiences are being developed.

The Skinner Device

Among the five initial devices (mock-ups) presented to you in December 1972 and reported on in our monthly letter No. 4 (dated January 31, 1973), one that was rejected by you was designed by Mr. Frank Skinner. This hand had three rotatable fingers, each having two bending joints. After leaving the project group, Mr. Skinner was encouraged first by Unimation Inc., builders of commercial robots, then by the Whirlpool Corp. to continue work on his concept. Two articles have appeared in the technical literature describing this:

a) "Design of a Multiple Prehension Manipulator System" by Frank Skinner. ASME Paper No. 74-DET-25, presented at the Design Engineering Technical Conference, October 6-9, 1974 in New York City. .

b) "Mechanical Hand with three fingers grasps heavy and fragile objects." Product Engineering magazine, February 1975, pages 16-17.

The original plastic model of the device described in these articles still lies in our laboratory here. It requires four motors to operate, one for each finger and one to orientate the fingers. A prototype is said to have been designed and tested by Whirlpool.

Finances and Contractual Arrangements

The project now completed cost almost double the amount of money allowed by NASA. There was no exact reckoning of the full cost because time and effort were given by full-time employees of the State, and by volunteers.

The policy of NASA to apply the same rules for reporting, etc. to a small project such as the one, as to a big project, was the direct cause of considerable hardships. If only one man is working on a project, the question continually arises whether he should work as designer and mechanic, or should write reports and keep financial records. This is the conflict of time and effort.

If NASA would have included the costs of a report-writing staff member, and more assistance in the contract, the whole conclusions of the work would have been very different and much faster. As it was, it all

turned rather sour, because there was no help and no money. We also had our problems, unexpectedly, in the main course of the development, chiefly the unfortunate disturbance caused by the rejection of Mr. Skinner's design, which he could not accept, and the heart attack suffered by Mr. Slobodyanik our chief designer.

We are happy now that the project is completed, and look forward to a report from you on the progress of the testing.

Design for a Three-fingered Hand

by

F.R. Erskine Crossley *

and

Franklyn G. Umholtz*

Abstract

This paper describes the construction of a prototype mechanical hand or "end effector" for use on a remotely controlled robot, but with possible application as a prosthetic device. An analysis of hand motions is reported, from which it is concluded that the two most important manipulations (apart from grasps) are to be able to pick up a tool and draw it into a nested grip against the palm, and to be able to hold a pistol-grip tool such as an electric drill and pull the trigger. One of our models was tested and found capable of both these operations.

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1. Introductory Considerations

The design of an artificial hand requires a blending of a number of important features. There is its kinematic form, which establishes its dexterity; its drive mechanisms and scale, which determine its strength and power; the available number and means of control of its input actuators, which constrain its usefulness; and the feedback sensors which determine its sensitivity or clumsiness.

The number of independent inputs that is available has been the greatest constraint. In medical prostheses scapular action has been the one fundamental means for operation: the patient has been enabled (by sticking out his shoulder-blade) to stretch a flexible cable to open or close the jaws of the artificial hand. Recently myoelectric signals have been used to control more driving motors, but there are problems in receiving good signals without cross-talk. On the other side, in designing manipulators for use in radioactive laboratories, for industrial and underwater purposes and for general research, the need has been for a whole arm and hand; thus it has usually been necessary to allot six independent degrees of freedom to the arm (shoulder, elbow and wrist), and the hand or "terminal device" has again been restricted almost invariably to one degree of freedom. The terminal device in these cases is usually a pair of jaws arranged for parallel action and capable only of being either opened or shut.

Various methods have been used for the continuous control of such a number of independent freedoms: the problem arises chiefly because an operator is not capable of deciding several questions simultaneously. The exoskeletal frame is one intermediary that makes use of our familiarity with moving our own arms in a co-ordinated manner. The shift-stick and the pistol-grip devices work because the six motions of the arm are correlated (through a computer) to the six degrees of freedom of a rigid body in space. To any one of these hardware devices it is possible to add fingertip controls; so it has become time to consider allowing a second or third degree of freedom to the hand or "terminal device" or "end effector". This was our task which is reported here.

Our focus was upon the kinematic arrangement and design of the mechanism only; for it was assumed that suitable activators and feedback sensors would be fitted wherever possible. The human hand has over twenty degrees of mobility. The present designs mostly have only one. Thus the problem simply put, is the following: if an end effector is to be designed with more than one degree of mobility, can there be a significant step-up of agility with one more, or are two or three more necessary, and then which of the freedoms of the hand are the next most valuable for inclusion in the robot?

A second question is this: should the design be conceived to pattern itself after the human model, or after some mechanical device such as a pair of tongs, or a chuck? To this there is one

obvious answer, that we are certainly most familiar with the utilization and exploitation of our hands, and therefore the more complicated the artificial hand becomes, the more desirable it is to be anthropomorphic.

2. Review of the State of the Art

A split hook such as the Dorrance hook is by far the most popular prosthetic device. Its kinematic action is simply scissor-like; however, when closed it also serves as a hook. On the other hand, the great majority of laboratory terminal devices have two symmetrically moving jaws, kept parallel to one another by two parallelograms of links, and no hook. Whereas the Dorrance hook is composed of only two pieces, the parallel jaws type is an assembly of at least seven pieces. Actuation is either by a tension cord, by a pair of quadrant gears, rack and pneumatic cylinder, or by electric motor, power screw and nut.

In prosthetic devices, the cosmetic aspect is often very important, and so the hand is made lifelike. The design problem is thus to drive five fingers by one input. The Northern Electric [1] hand and the Becker hand [2] are typical (from the kinematic viewpoint) of the simple form. The fingers are attached by springs to an equalizing lever or coupled by friction clutches to one another. The thumb is either stiff, or it has one or two positions which can be preset.

The Tomovic (Yugoslavian) hand [3] uses a motor, power screw and nut all inside the palm to pull on an equalizing lever held by springs. This first lever in turn balances two secondary equalizing levers, the four ends then pulling on the four fingers. The finger mechanization is of the crossed-four-bar type and induces flexure of the metacarpal-phalangeal joints and the proximal phalangeal finger joints. The springs and the branched tree-form of drive allows the fingers to adjust themselves to holding either a ball or cylindrical object. The Yakobson (Russian) patent [4] is similar though it contains two motors, one for the four digits, the other to move the thumb independently.

A Swedish design [5] uses a tendon cord to drive each finger, the cords being wound upon spools driven by electric motors, EMG controlled.

At Waseda University, Japan, Kato and his colleagues have produced at least three designs of hands for prosthesis [6], with EMG signals as input. Mori and Yamashita in Tokyo [7] have an extraordinary device, consisting of three fingers, each having three joints and thereby three degrees of freedom independently motorized and operated by computer, which is agile enough to twirl a baton.

More than one degree of freedom has been designed also into a few industrial manipulators. Dane of NASA/MSFC [8] has invented a thin trigger finger which can emerge from one side of a parallel-clamp; the device can hold an electric drill by its pistol grip and

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operate it by pulling the trigger. A group of students under Hill [9] devised a terminal device with three degrees of freedom. Two stiff parallel fingers, on variable center distance, form with a thumb a three-jaw chuck. The thumb has three joints, which allow it to perform as a hook, or to get out of the way. Another three-fingered design is due to Kleinwächter.

Tomovic has described the philosophy behind the design of the Belgrade hand, that, because any operator will have difficulty in deciding the courses of several movements simultaneously, so the hand itself should be capable of adapting itself to pick up different objects, subject only to one decision of the operator to grasp.

Somewhat analogous to the spring-restrained tree mechanism of the Belgrade hand are the several forms of the Goodrich "Elastolift" grab [10]. Each finger of these devices is like a piece of hose, finger long and sealed at its end, which is ribbed along one side so that when pneumatic pressure is introduced inside, the finger curls. As it must stop when it contacts a body to grasp, it is also self-adjusting to any shape of object.

3. Manipulation

It is recognized that in the large majority of instances one's hand is used only to grasp. It must also adjust its shape to the form of the object to be held, and in this Schlesinger's six forms of prehension [11] are well-known: these show the hand conforming

itself to wrap around a cylindrical body or pipe, to hold a ball, to hook on to a baggage handle, to hold a pill between two fingertips, to hold a pen and to proffer a plate or grip a paper.

The typical parallel-jaw end-effector of a robot arm has been remarkably satisfactory in a laboratory milieu for picking up all sorts of objects. Its shortcomings however have been whimsically compared to those of a garage mechanic who was forced always to use only a pair of pliers to do his work, even to the extent that, if he wished to use a screwdriver, he had to hold it with the pliers. This is the problem with the robot's jaws, that there is no encircling grasp by which to exert torque.

Table 1 shows a new listing of functions that can be performed by the hand in office or laboratory. These have first been differentiated by whether they are static grasps only, or whether they involve a manipulation. Here a "manipulation" is defined as a function of the hand (not the arm or wrist) requiring a movement of the fingers (and probably also a movement of the object held or touched) relative to the centroid of the hand.

It may be noticed that a few extra static grasps have been identified which might be added to Schlesinger's six forms. They are items nos. 9, 10, 14, 15, 22 and 27. But these are minor.

From this list we now extract and list separately in Table 2 the manipulations, and analyse these with some care to see what is the number of fingers in action to achieve each purpose.

TABLE 1: HAND ACTIONS

Position	Action	Grasp or Manip.	Description
1.	Pen hold	Grasp	Three-point chuck grip plus support in thumb Y.
2.	Pen write	Manip.	Bending of all three fingers while in position #1.
3.	Pen Screw	Manip.	Bending of index finger; thumb held stiff.
4.	Screwdriver	Grasp	Three-point grasp plus support from ball of thumb.
4.A.	Screwdriver	Grasp	Screwing rotation derives from wrist.
5.	Paper hold	Grasp	Index lateral, tee-position to thumb
6.	Cigarette roll	Manip.	As #5 with index finger bending, thumb stiff.
7.	Pipe hold (transverse)	Grasp	Thumb, palm and fingers (pipe at 90° to arm).
8.	Hose bayonet lock	Grasp	As #7 with wrist action.
9.	Hammer hold (longitudinal)	Grasp	Similar to #4 (cylindrical handle's axis parallel to arm)
10.	Ice pick grip	Grasp	As #7 with thumb for end pressure
11.	Spherical	Grasp	At least three fingers to curl around
12.	Fingertip (two point)	Grasp	Such as used to pick up a pill, two fingers only
12.A.	Fingertip (three point)	Grasp	Such as used to pick up a pencil on a table. Two finger tips and thumb
13.	Handle hook	Grasp	Thumb adducted dorsally
14.	Discus hook	Grasp	Limit of #13: fingers 3,4,5 against palm
15.	Tripod support	Static	Pressure by three fingertips against panel
16.	Wrench grip	Grasp	As #7 or #4
16.A.	Wrench grip	Grasp	Dynamic action derives from wrist
17.	Wipe	Grasp	As #11, using cloth in place of ball
18.	Indicate, Poke	Static	One finger extended (for telephone dialing)
19.	Trigger grip	Manip.	As #10, but index finger reaches and pulls.
20.	Electric lamp switch	Grasp	As #7, but delayed squeeze of #3 finger
21.	Typewrite	Manip.	Individual finger motions
22.	Fist	Grasp	Limit of #11, Thumb overlapping fingers
23.	Doorknob	Grasp	As #8
24.	Cup handle	Grasp	As #5, with vertical orientation

TABLE 1: HAND ACTIONS.

<u>Position</u>	<u>Action</u>	<u>Grasp or Manip.</u>	<u>Description</u>
25.	Transfer pipe to grip	Manip.	(e.g. Transfer pencil from fingertip pick-up (#12A) to palmar grip #7) by a clambering movement of fingers 4 and 5
26	Pen transfer	Manip.	Pen picked up and held (pivotally) by thumb and index. #3 finger distal phalanx (lateral) used as pusher to swing pen into thumb Y
27	Pick up	Grasp	Medium sized (e.g. cigarette box) Object pressed against palm and ball of thumb by fingers 4 and 5, as in #9
28	Use cutters	Manip.	As grasp #27 but opening and closing grip against spring-action of cutters.
29	Flip switch	Manip.	Not unlike trigger (#19) but without also grasp
30	Pushbutton	Static	As #18 with arm motion

TABLE 2: MANIPULATIONS

Item	Action	Comment
A	Trigger grip	Index finger reaches out, hooks, draws back, while thumb and fingers 3, 4, 5 grasp object.
B	Flipping a switch	Index finger reaches out, pulls back (similar to A) while other fingers rest.
C	Transfer pipe to grip	The inverse of #A. Thumb and index grasp an object lightly while fingers 4 and 5 reach out, hook and draw back.
D	Use cutters	This requires no independent finger motions.
E	Pen screw	It is a grasp on an object of varying width. Thumb held stiff. Index finger bends. Tip of index used to roll object down palmar surface of thumb.
F	Cigarette roll	As in E, but lateral surface of index finger used.
G	Pen transfer	Similar to, but reverse of C. Thumb and index grasp, then finger 3 hooks under object and pushes away.
H	Type write	(Or selecting from an array of buttons a sequence to push independently.)
J	Pen write	It is possible to achieve this movement of the object by moving the whole forearm instead of bending the fingers.

Manipulations A and B are similar, and require the independent movement of one finger, usually the index. This function is a most important one where mechanical tools such as an electric drill might need to be used.

Manipulation C is also of very great value, if it can be achieved, because it allows the nesting of hand tools such as a wrench in the palm of the hand, so that a torque can be exerted.

An alternative method of providing torque is to use specially shaped tools, such as the Tee-bar handle on some undersea manipulator tools; this entails a hope that the tool can be knocked into the complementary socket of the end effector. Dow Chemical (Rocky Flats) have also devised shallow recesses in the parallel jaws of their pneumatic end-effector, which fit the hexagonal section of the handles of special accessory tools. The design is named the Wedge-grip.

Another possible approach, instead of drawing the tool or object down to the palm, is to raise the palm up between the fingers, to contact and support the object while it is still held at fingertips.

Manipulation D is easy to accomplish, provided the tool does not drop out during the opening movement. Some tool recess, hook, groove or other attachment is desirable.

Manipulations E and F are probably out of reach, and not of great value. Manipulation G is a variation on C and of doubtful value. H requires many independent drives, thus a heavy hand, full of motors and this is out of reach. Action J can be achieved without manipulation.

Thus the emphasis can be on a design which can achieve actions A and C, while still also performing satisfactorily as the customary pair of parallel jaws. In order that A shall be useful, the cylindrical grasp (Table 1, item 7) is also necessary. As in both the manipulations A and C only one independently moving finger is needed, therefore a design should be realisable that consists of two fingers and a thumb.

Let us look again at these manipulations A and C from the standpoint of an assumption that this shall be three-fingered hand. Let us call these three the thumb, index and ring fingers. In manipulation A (trigger) the thumb is placed opposite to the ring finger, applying a grip, and the index finger then works independently. In manipulation C (transfer) the thumb is set opposite to the index, and ring finger works independently. In a non-human case this is a distinction only of right and left; there need be no difference between the index and ring fingers, rather like in the Stanford design (ref. 9). Stated in another way, it should be possible to design pistol-grip tools like electric drills, such that the trigger be lower in the grip, where it can be squeezed by the ring finger while thumb and forefinger grip the handle. In order that a robot could use such a tool (with the trigger placed in this manner) it would be necessary for the terminal device to have exactly the same form as for manipulation C. It would then be unnecessary for the thumb to move its position from being in apposition to the index to being in apposition to the ring finger.

4. Details of the Hardware

Number of Digits. The conclusion was to design an end effector with three digits, that is, a thumb and two fingers. The third finger needs to be separately motorized for trigger action. If the thumb and index are to work only in apposition, one motor should suffice for these. But if the hand is to provide the "hook" or "baggage lift" capability, the thumb needs to be left fully open while the index finger closes. This means either three independent motors, or two motors and a clutch.

Anthropomorphism. It was decided that the hand should follow the anthropomorphic model as much as possible for two reasons. Firstly the immediate task was for an end-effector for use on a remote manipulator in space, viewed by the operator only through television cameras and screens. As the end effector is to be more complicated than simple jaws, then it may be confusing to the operator both to watch and to use, except if he can imagine his own hands projected there and rely on his built-in sense of feel to perform each task. The second reason is that a successful anthropomorphic form of hand has potential as a prosthetic device also.

This decision carried over to provide the reason for setting the main transverse axis of the palm at 45° to the longitudinal axis of the fore-arm and wrist. (See Figure 1)

Finger-bending Mechanism. A unique method of bending the inter-phalangeal joints was worked out, which has two very important advantages; that the mechanical advantage is upheld from the motor right to the joint, the velocity reduction and force augmentation being at the last possible

moment; and secondly, that the high forces to be encountered in the joint are combined with their reactions into a small triangle at each pivot.

Figure 2 shows the scheme of these joints. The two phalanges, being of channel form, are directly hinged. The two are also connected by a turnbuckle, with right and left-hand threaded eye-bolts. The buckle itself is a pinion, and driven by another pinion through a flexible cable within the finger. The other end of this cable can be driven directly by the motor through a reduction gear.

By this design the moments of any lateral force imposed at the finger tip is carried by the structure of each phalanx and the joints, but it is not felt by the finger drive mechanism, except as a much reduced torque, and then only when the pinion turns, for the pitch of the screws makes the drive irreversible.

The first model made was able to produce a pinch force at the fingertips of 10.5 kilograms. The final model produced less, about 6 kg.

Fingertip Parallelism. The parallel-jaw end effector has been an accepted form for so long, that any new device is certain to be compared with it as a norm of dexterity. For this reason it was decided that this new device should include a parallel-jaw pair. A set of parallelogram four-bar linkages in cascade are mounted in the side plates of both thumb and index finger. Their effect is to maintain the inside (gripping) surfaces of the ultimate phalanges of these two digits parallel to one another and perpendicular to the surface of the palm, even while the more proximal phalanges bend to form a cylindrical grip.

Finger Surfaces. It is thought to be important for the gripping surfaces of the fingertips of the model to be cushioned (to accommodate themselves to various shapes to be grasped) and to have as high a coefficient of friction as possible. The inside gripping surfaces are covered with a layer about 3 mm. thick of soft silicone rubber, cast in place. This material does not adhere to a metal surface, therefore before casting, the metal pressure plate was drilled with many holes, of 2 mm. diameter, and the plastic cast as a sandwich on both sides of the metal, through the holes and around the ends. With this method, the padding held itself firmly in place even when heavily strained.

Thumb Nail. On our penultimate model a "thumb nail" was added to the thumb, which permitted the operator successfully to pick up a thin metal rule lying flat on a table, and also to pick up a number of other objects by getting the "nail" under them. It held a remarkable advantage.

The nail was merely a metal plate, 1.5 mm. thick with a serrated edge, of the width of the thumb (2 cm), and projecting 2 cm from the end of the distal phalanx. Before building the final model the opinion was voiced that this nail might interfere with the grip; therefore it should be made retractable. This was done. The nail slides in curved guiding grooves, and is moved by a small motor. Unfortunately, there was insufficient space for this afterthought, and the motor protrudes a little into the palm when the thumb is fully open. The retraction works very well, but brings with it two disadvantages: added total weight of the hand and one additional control to be operated.

Assembly. This is shown in Figure 3. It is constructed mostly of magnesium, and contains more metal than it should, because it was decided that all the mechanisms involved should be enclosed. This adds considerably to the total weight.

Control System. The controls were a set of four miniature two-way switches and three on-off buttons, arranged on an arched plate for contact with four fingertips. It was felt to be important to divide the controls into "preselections" and "operate commands."

The two-way switches provided for the following preselections:

- 1) Thumb nail: run out or run back.
- 2) Third finger: motor to be in forward or reverse mode.
- 3) Thumb and index: both to run together, or independently.
- 4) Thumb and index: both motors to be in forward or reverse.

The button switches on the other hand introduced the commands to run (in the modes preselected) and so are connected in series with 2, 3, 4 above.

- 2) Third finger motor: run.
- 3) Index finger motor: run (This button is cut out of the circuit if switch (3) selects "together")
- 4) Thumb motor: run (or if switch (3) is set in "together" position, this button starts both thumb and index finger motors.)

5. Tested Capabilities

The best performance was recorded by the penultimate model rather than the final one. This model was not mounted on a robot arm but arranged to be

worn as a metal gauntlet on the hand. The operator's hand can be inserted in the hollow palm, and the motor control switches are located there. The metal fingers are not hollow. This model was tested extensively and its capabilities were impressive; the following tasks were accomplished at one time:

- Picked up a 25 cm length of 5 x 8 cm section wood with the end effector;
- Picked up a C-clamp, and (using a human hand to hold this clamp) used the end effector to turn the wing-nut to screw the piece of wood down;
- Picked up a hammer from the table, used the third finger to draw it into a palmar grip;
- Used the hammer to drive a heavy nail into the wood; the grip was sufficiently tight to hold the hammer without shifting during this exercise;
- Picked up a portable pistol-grip electric drill;
- Pulled the trigger by the first finger, and held the drill while it drilled a 1/2 inch hole in the wood;
- Picked up a needle from a flat metal-topped table;
- Picked up a triangular inch-wide wooden draftsman's scale from the table and transferred it into palmar grip;
- Picked up an open-ended 3/8 inch wrench; transferred it to palmar grip; then used it to tighten a bolt head;
- Picked up a 5 cm. wide, 1/4 mm. thick, sheet-metal rule which was lying flat on a table top; transferred it to a firm fingertip grip;

- Picked up and held firmly a 8.5 cm. diameter spherical ball;
- Picked up a camera (Kodak Instamatic) and by means of the third finger actuated the shutter to take a picture;
- Took hold of a door knob and opened a door;
- Took hold of a half-pint mechanic's oil can and squeezed its trigger to actuate it;
- Pulled open a desk drawer by the handle;
- Picked up a cupboard key from a table, inserted the key, unlocked the cupboard, and opened its door, then removed one "magic marker" crayon from a closely spaced magazine of crayons.

It is easier to operate a mechanical hand when it is held in this manner, than when it is mounted on a mechanical arm. The final model made was designed to be mounted on such an arm, but up to the present it has not been tested on an appropriate one.

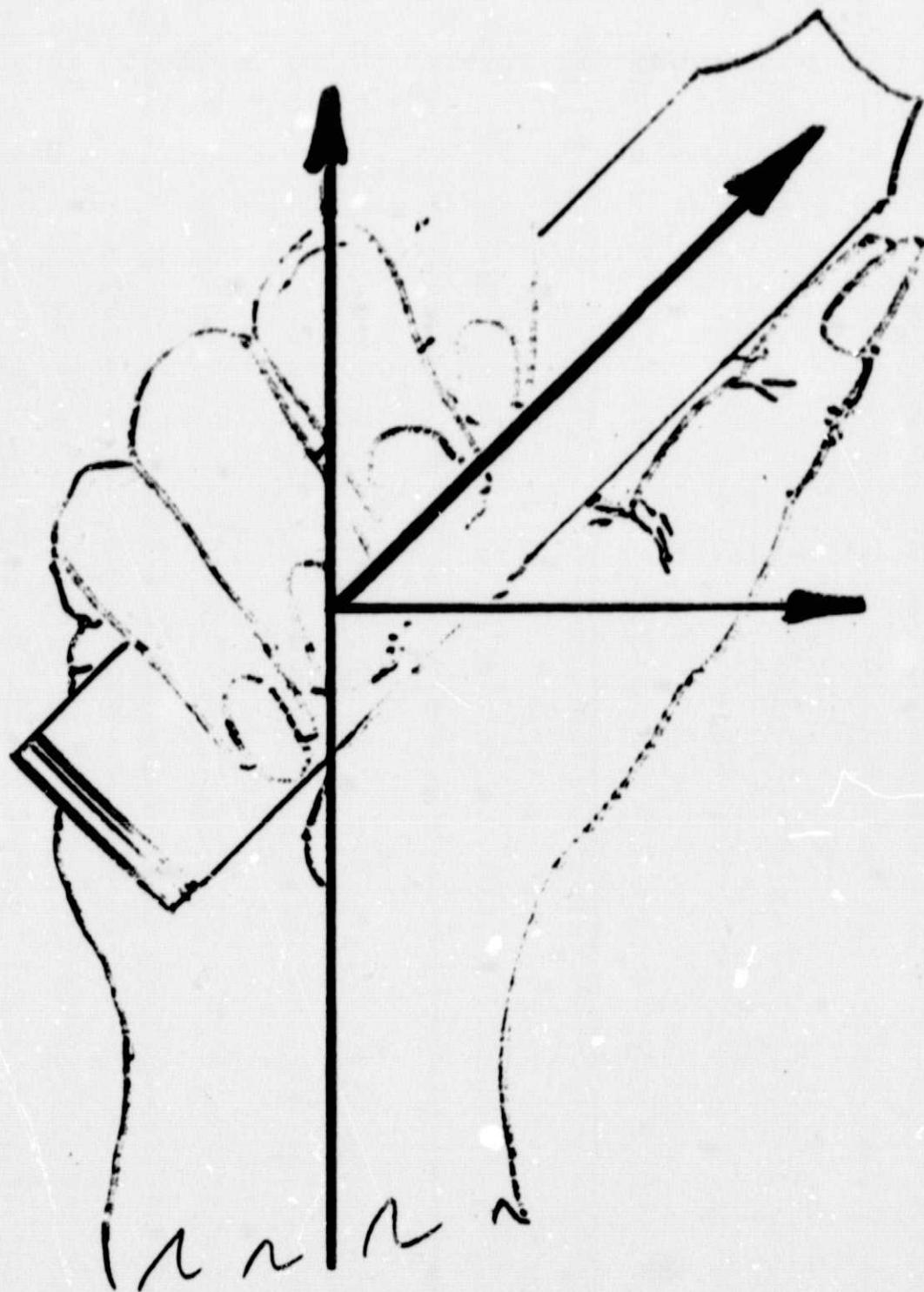
The final model differed from the penultimate one in a number of small but significant details: the motor gear ratios had rather less reduction than formerly, so that the fingers worked faster but with less force. The placement of the finger pivots was changed very slightly, with the result that the fist or closed fingers position was considerably less tight, and moreover the joint linkage in the most distal joints came too nearly to their dead-center positions, so that the end joints could wobble. The flexible cable drives to the turnbuckles inside the fingers worked less freely in the final model than in the earlier, and were converted from a series drive to a parallel drive system. These are the details. A real prototype is never expected to be quite in conformity with everything planned for it.

Acknowledgements

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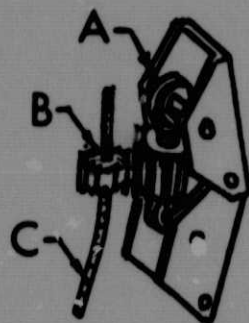


Figure 2: Detail of Finger Turnbuckle Mechanism.
A - Eye bolt, B - Finion Drive, C - Flexible cable.

